Highly Directive Array Pattern Synthesis in Different φ Planes of a Large Concentric Circular Ring Antenna Array (CCRAA) Using Array Thinning Technique

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ABSTRACT This paper presents a pattern synthesis method of a sizeable concentric circular ring array (CCRAA) of isotropic antennas using Evolutionary Algorithms. In this method, the array is thinned using the optimum set of binary excitations to achieve the desired highly directive pencil beam patterns with lower peak side lobe level(SLL). The half-power beam width and first null beam width is kept constant to obtain such highly directive beam patterns with lower peak SLL. This pattern is not synthesized to a particular azimuth plane rather in four different φ planes from entire azimuth planes. The isotropic elements are uniformly spaced in the concentric ring. The achieved set of optimum amplitudes are constructed with either 1 or 0 using Differential Evolutionary Algorithm(DE), Genetic Algorithm (GA), and Particle Swarm Optimization Algorithm (PSO). These excitations show the state of the elements. The elements are in "ON" state or in "OFF" state depending upon the excitation '1' or '0'. It is also helpful to reduce the complexity of the feed networks. The excitations are also verified in the whole range ($0^o \leqslant \varphi \leqslant 360^o$) of φ planes by selecting four φ planes arbitrarily. The outcomes established the superiority of GA and DE over PSO and also the effectiveness of the proposed method.

INDEX TERMS Array Synthesis, Array Thinning, Binary Excitation, concentric circular ring array (CCRAA), Evolutionary Algorithm, Wilcoxon rank-sum test.

I. INTRODUCTION

THE sizeable concentric circular ring array antenna (CCRAA) having high directivity with lower SLL is handy in satellite, radar, and wireless communication for the azimuthal symmetry of the pattern [1]–[4]. However, the beam at a range of azimuth planes with high directivity faced a serious sidelobe problem. Various approaches reported in different literature for generating the array patterns using thinning are as follows [5]–[12].

Sherman et al. presented a thinning method where a large planner array of 10000 elements are thinned, and after thinning of 90 percent, i.e., only 1000 element produces the beam pattern with entire main lobe width and lower peak SLL [5]. Chatterjee et al. proposed and developed a process for generating a pencil beam pattern by applying the binary firefly and binary Particle Swarm Optimization algorithm (PSO) [6]in various predefined φ plane. Dessouky et al. applied a technique to find out the steering matrix and gain from a small concentric ring array with central element feeding where the elements are spaced at an equal distance of 0.5λ [7]. The authors Dessouky et al. proposed another method where the tapering window helps achieve the beam pattern having lower peak SLL. For compensating the gain reduction, the tapering window can be modified and compared to the uniform excitation [8], [9]. R.L Haupt proposed a pattern synthesis technique where the elements are placed optimally in the concentric ring array [10]. The same author proposed another thinning method using a binary Genetic Algorithm of a nine-ring concentric circular ring array antenna [11]. N. Pathak et al. proposed a thinning method by keeping the inter-element spacing fixed and variable and comparing the outcomes with the fully populated array using particle swarm optimization algorithm (PSO) [12]. M. Fernandez-Delgado et al. use an approach that aggregates the commitment of each array member towards the far-field pattern to increase the mathematical effectiveness of the optimization process [13]. Jain & mani proposed a procedure of doing thinning within real life situations is referred to as dynamic thinning. Its

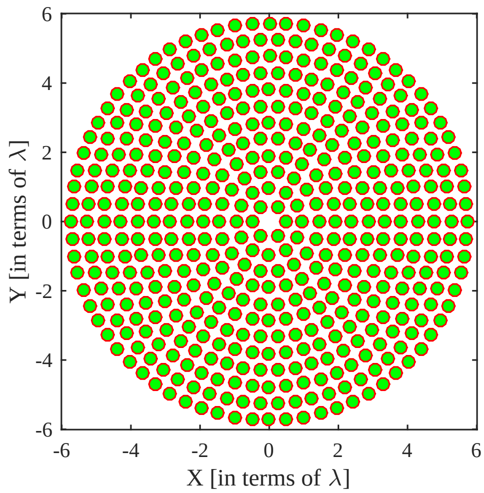

FIGURE 1: Geometry of fully populated CCRAA.

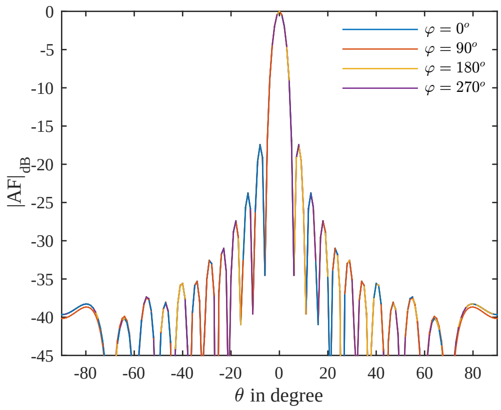

FIGURE 2: Array factor of fully populated Array

designing of thinning arrays has benefited from randomized approaches. Nevertheless, when implementing the approach to big 2-D arrays, issues develop owing of the highly wide potentially rugged solution space, which causes difficulty in new conditions [14]. The concept of utilizing an optimization algorithms towards array thinning is also discussed by Jain and Mani. Following through the fundamentals of array thinning, dynamic thinning, and implementation technique, simulated results while using the approach both linear & planar arrays [15].

In this paper, a pencil beam pattern from a CCRA antenna of 12 rings with 468 isotropic elements are considered the optimum set of normalized amplitudes are computed using Evolutionary Algorithms. Here the excitations are computed using Evolutionary Algorithms that are binary, so the elements having amplitude ‘ 1’ is in the “ON” state, and those elements are considered as “OFF” whose excitation is zero. The patterns have been generated in four predefined azimuth planes using the binary excitations achieved by DE, GA, and PSO. This technique also verifies that the pattern retains its desired sidelobe level within entire range of φ

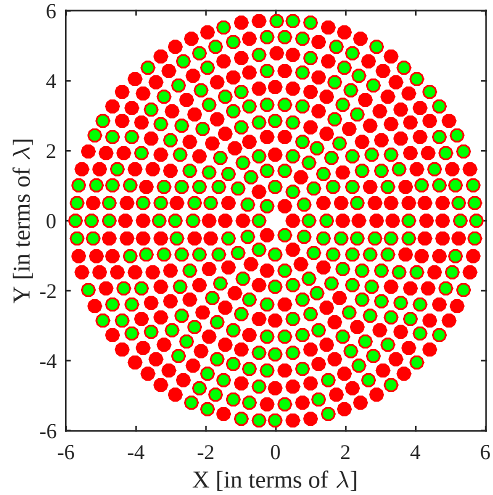

FIGURE 3: Thinned CCRAA using DE

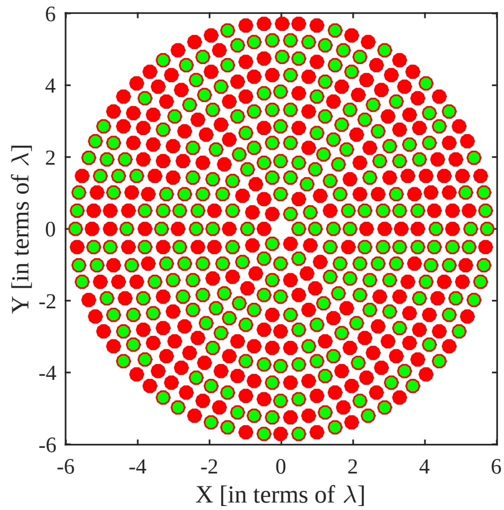

FIGURE 4: Thinned CCRAA using GA

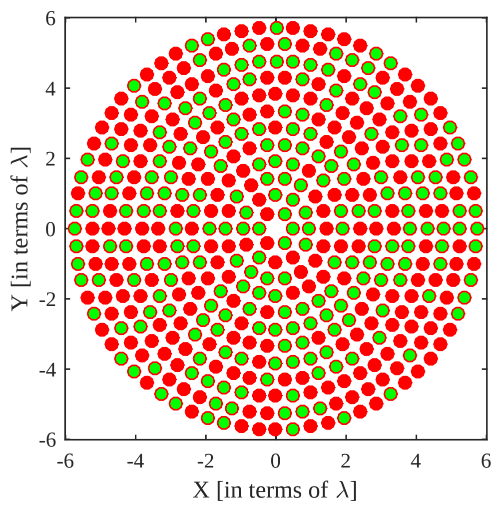

FIGURE 5: Thinned CCRAA using PSO

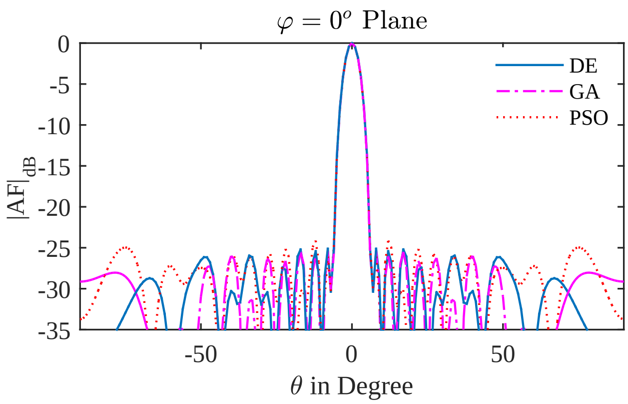

FIGURE 6: Obtained pattern at $\varphi = 0^o$ Plane

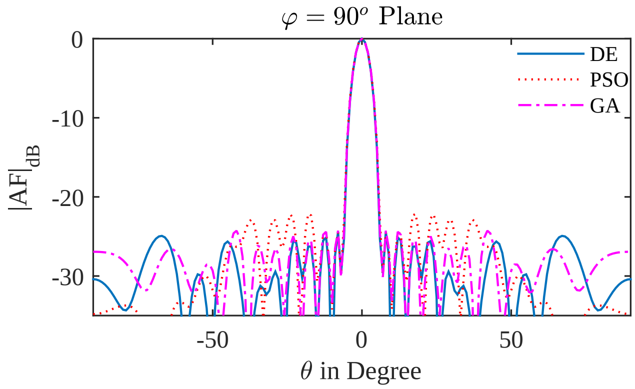

FIGURE 7: Obtained pattern at $\varphi = 90^o$ Plane

planes. After selecting some arbitrary azimuth planes, the achieved patterns depicted similarity with some minor variations. These binary excitations are helpful to minimize the design complexity of the attenuator. The achieved directivity of the thinned array is very high with lower SLL. The comparative performance of three Evolutionary Algorithms, Differential Evolution algorithms (DE), Genetic Algorithm (GA), Particle Swarm optimization algorithms (PSO) is also analyzed.

II. PROBLEM FORMULATIONS

A concentric circular ring array of twelve rings is considered. The far-field pattern of the CCRA is depicted in Figure 1 can be written as [1], [2]:

$$AF(\theta, \varphi) = \sum_{m=1}^{M} \sum_{n=1}^{N} I_{mn} e^{jkr_m sin\theta cos(\varphi - \varphi_{mn})} \quad (1)$$

Normalized power pattern $AF(\theta, \varphi)$ in dB.

$$P(\theta, \varphi) = 10log_{10}\left[\frac{|AF(\theta, \varphi)|}{AF(\theta, \varphi)_{max}}\right]^2 = 20log_{10}\left[\frac{|AF(\theta, \varphi)|}{AF(\theta, \varphi)_{max}}\right] \quad (2)$$

Normalized Radiation Pattern can be written as

$$AF_n(\theta, \phi) = \left[\frac{AF(\theta, \varphi)}{AF(\theta, \varphi)_{max}}\right] \quad (3)$$

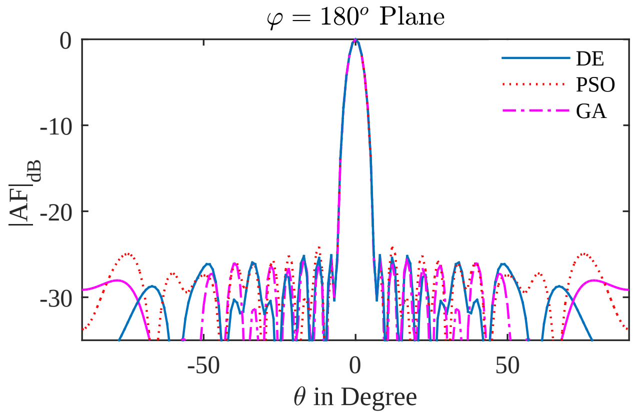

FIGURE 8: Obtained pattern at $\varphi = 180^o$ Plane

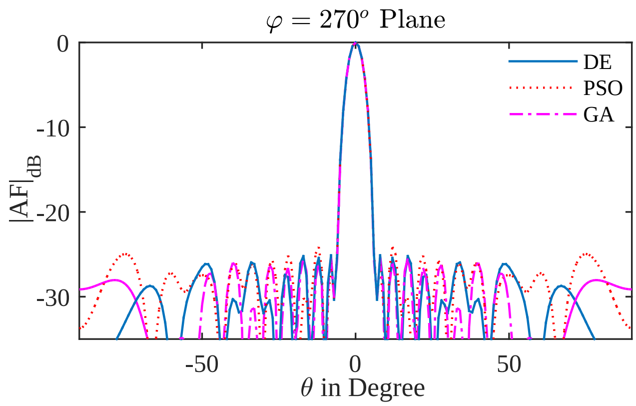

FIGURE 9: Obtained pattern at $\varphi = 270^o$ Plane

Here,
M = Number of concentric rings;
N_m = Number of isotropic elements in m-th ring;
I_{mn} = Excitation amplitude of mn -th element, which is zero if "OFF" and one if "ON";
d_m = Inter element arc spacing (0.5λ);
θ, φ = polar and azimuth angle;
$\varphi_{mn} = 2n\pi/N_m$ the angular position of mn-th element, where $1 \leq n \leq N_m$
$r_m = N_m d_m / 2\pi$ Radius of m-th ring;
$k = \frac{2\pi}{\lambda}$ is the Wave number;

The fitness function for the pattern is defined as:

$$F(\rho) = k_1 \left[peakSLL_{\varphi}^{d} - max_{\theta \in A}\left\{AF_{dB}^{\rho}(\theta, \varphi)\right\}\right]^2 H(X) \quad (4)$$

The directivity can be written as:

$$D = \left[\frac{4\pi}{\int_{\theta=0}^{\pi}\int_{\varphi=0}^{2\pi}|AF_n(\theta, \varphi)|^2 sin\theta d\theta d\varphi}\right] \quad (5)$$

In equation, 4 $\varphi \in (0^o - 270^o)$ plane.

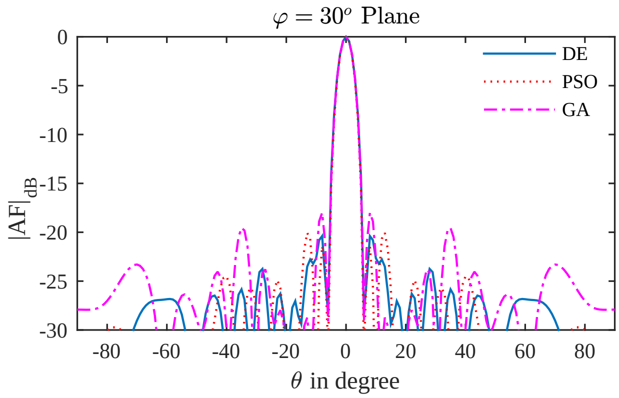

FIGURE 10: Obtained pattern at $\varphi = 30^o$ Plane

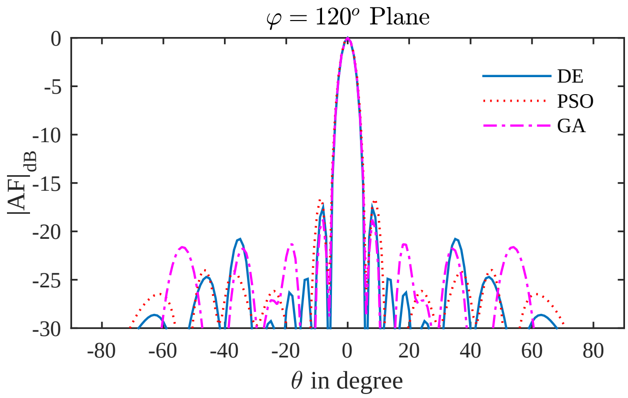

FIGURE 11: Obtained pattern at $\varphi = 120^o$ Plane

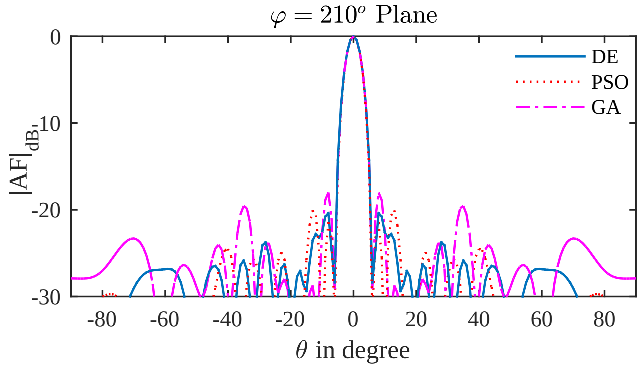

FIGURE 12: Obtained pattern at $\varphi = 210^o$ Plane

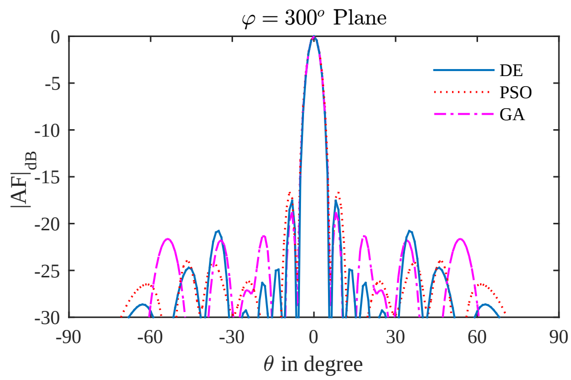

FIGURE 13: Obtained pattern at $\varphi = 300^o$ Plane

ρ is the unknown parameter set which is responsible for the desired beam pattern for this approach. ρ is defined as follows:

$$\rho = \{I_{mn}\}; \tag{6}$$

where, $1 \leq m \leq M$ and $1 \leq n \leq N_m$
$H(X)$ is Heaviside step function can be defined as follows

$$X = \left[peakSLL_{\varphi}^{d} - max_{\theta \in A}\left\{AF_{dB}^{\rho}(\theta, \varphi)\right\}\right] \tag{7}$$

$$X = \begin{cases} 1 & if, \quad X \geq 0 \\ 0 & if, \quad X < 0 \end{cases} \tag{8}$$

$peakSLL_{\varphi}^{d}$ is a vector containing the desired values of all the peak SLL in their corresponding φ cuts. The term $max_{\theta \in A}\left\{AF_{dB}^{\rho}(\theta, \varphi)\right\}$ in equations 4, denotes the maximum value of side lobe level in all the predefined φ planes in A (side lobe region). Where $\varphi = 0^o, 90^o, 180^o$ and 270^o plane and k_1 is the weighting factors. The number of elements who have no contribution to construct beam pattern after thinning in comparison with the total number of array elements can be determine using tapper efficiency η_{ar} [7]. An array taper efficiency can be expressed using the following equation.

$$\eta_{ar} = \left(\frac{Number\ of\ elements\ turned\ off}{Total\ number\ of\ elements\ in\ the\ array} \times 100\right)\% \tag{9}$$

For the optimal synthesis of the pattern, the fitness function given in equation 4 has to be minimized. In this article, Genetic Algorithm (GA), Particle Swarm Optimization Algorithm (PSO), and Differential Evolution Algorithm (DE) has been applied to minimize the fitness function.

III. RESULTS

A concentric circular ring array of twelve rings with 468 uniformly placed isotropic elements has been considered. Where $(r_m(\lambda))$ is the ring radius, N_m is the number of isotropic elements in the m-th ring, and M = 12 is the total number of rings chosen. The inter-element arc spacing is considered as 0.5 λ. As shown in Figure 1. The number of the isotropic element present in each ring with the value of ring radius is mentioned in Table 1.

From Table 1, it can be seen that in the first ring, six elements are present and the radius of the ring is 0.4775 λ. Similarly, in the last ring, i.e., in ring number 12, there is seventy-two isotropic elements are present with ring radius 5.7296 λ.

The excitation amplitudes of the CCRAA are given in Table 2. Here the optimum binary excitations are computed using three different Evolutionary Algorithms (EA). These

TABLE 1: Ring radius and number of elements per ring

Ring Number(M)	1	2	3	4
Radius $(r_m(\lambda))$	0.4775	0.9549	1.4324	1.9099
Number of Elements (N_m)	6	12	18	24
Ring Number(M)	5	6	7	8
Radius $(r_m(\lambda))$	2.3873	2.8648	3.3423	3.8197
Number of Elements (N_m)	30	36	42	48
Ring Number(M)	9	10	11	12
Radius $(r_m(\lambda))$	4.2972	4.7746	5.2521	5.7296
Number of Elements (N_m)	54	60	66	72

algorithms are Differential Evolution Algorithm (DE), Genetic Algorithm (GA), and Particle Swarm Optimization Algorithm (PSO). The amplitude '1' shows that the element is in the "ON" state, and those elements having '0' amplitude are in the "OFF" state. In Figure 3, Figure 4, and Figure 5, the elements depicted using green color are in "ON" state, whereas the elements in red color are in "OFF" state. The optimum excitations for which the array produced the lowest peak SLL are given in Table 2 for each Evolutionary Algorithms (EA).

In Table 3, it can be observed that the pattern is synthesized in four predefined azimuth planes using three Evolutionary Algorithms. These four predefined φ planes are $0^o, 90^o, 180^o,$ and 270^o. The desired value of peak SLL are $30dB$ for all azimuth planes. By using the optimum binary excitations, which is achieved from DE, the obtained values of peak SLL are -25.0932dB at $\varphi = 0^o$, -24.4202dB at $\varphi = 90^o$, -25.0932dB at $\varphi = 180^o$ and -24.4202 dB at $\varphi = 270^o$. Similarly, by applying GA, the achieved optimum binary excitations are used to get the beam pattern with minimum peak SLL. The values of peak SLL at the same predefined azimuth planes are -25.3927dB, -24.2762dB,-25.3927dB and -24.2762dB respectively at $\varphi = 0^o, 90^o, 180^o,$ and 270^o. These results are also compared with PSO. The value of peak SLL for fully populated array is -17.4566 dB, and directivity is 34.9219. The array factor for fully populated array in all predefined φ plane is shown in Figure 2. The thinning percentage or Tapper efficiency is also computed, and the values are 47, 48.07, and 51.28 for DE,GA, and PSO, respectively. The array factor is shown in Figure 6, Figure 7, Figure 8, and Figure 9. From the last column of Table 3, it can be seen that the directivity of the beam pattern using DE is 29.4935, using Ga is 29.5269, and PSO is 28.6952.

In Figures 10, 11, 12, and 13, beam patterns generates in four arbitrarily chosen φ planes for the same excitations with some minor variation. In each Figure, the 1st arbitrary azimuth angle is chosen as 30^o degree ($0^o < 30^o < 90^o$), which is in between the predefined φ plane, the second one is 120^o (within the predefined φ plane 90^o, and 180^o), and the 3rd one is 210^o ($180^o < 210^o < 270^o$) the last one is 300^o which is in between ($270^o < 300^o < 360^o$) the predefined φ plane.

In Table 4, the values of peak SLL are shown in all the arbitrary angles for all three EA. The obtained values of peak SLL for arbitrarily chosen azimuth planes and predefined azimuth planes are comparable. In this array thinning method, all the azimuth planes are not considered; rather, some predefined azimuth planes are taken into account.That ensures a range where the patterns retain their characteristic. Figure 14 shows the convergence curve of DE, GA, and PSO. From this convergence curve, it is clearly observed that GA is superior in comparison with DE and PSO as fitness value of GA is lesser than the others. The Computations have been done in MATLAB 2015a with core 2 duo processor, 3GHz, 4GB RAM.

Table 5 compares the design issues in the best fitness values (out of 20 distinct runs), worse value, mean value, and standard deviation of DE, GA, and PSO performance. The lowest value of fitness i.e., the best fitness value of DE, GA, and PSO are 103.3645, 96.449, and 165.1119. which indicates that the GA is the best performing algorithm for the problem presented.Table 6 shows the values obtained by the Wilcoxon rank-sum test between the GA /DE and GA / PSO pairs for these design considerations. The obtained values are less than 0.05 (5% significance level) is the powerful evidence of the null hypothesis that the best fitness value achieved by the best algorithm is statistically significant.

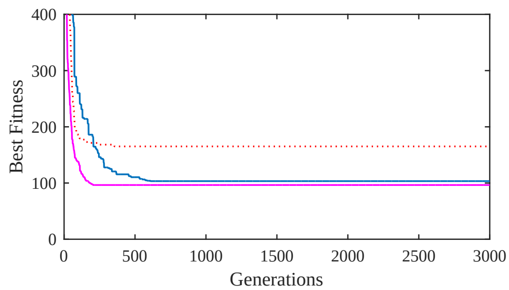

FIGURE 14: Convergence curve of all three Algorithms.

IV. CONCLUSION

A highly directive pencil beam pattern of a large concentric circular array antenna has been synthesized in four different azimuth angles from whole azimuth planes. The beam pattern is synthesized in four predefined azimuth planes using three well-known Evolutionary Algorithms. Each Evolutionary Algorithm generates binary excitation to achieve the desired parameter. The relatively similar pattern in arbitrary planes shows that the beam pattern with the desired parameter is not only in the predefined azimuth planes rather the entire range of azimuth planes. Keeping HPBW and FNBW constant, the design parameter, peak sidelobe level (peak SLL) is reduced by finding the optimum set of binary array excitations using DE, GA, and PSO. This array thinning is also reduced the design complexity of the attenuator in the feed network. This array thinning of pencil Beam Pattern also ensures that the desired patterns retain their specification with some minor variations in the whole range of azimuth planes. The performance of GA and DE are comparable and far better than PSO. This thinning method can also be used to synthesize other array geometries.

TABLE 2: Excitation Amplitude distribution (I_{mn}) of thinned array

Ring Number	DE	GA	PSO
1	001101	110010	110101
2	111101011101	110100101110	111101101001
3	101011110011001011	100111001011010001	000111010101111000
4	001111011111001010111011	111111111110101001100110	110101110000100011100010
5	011011100001111101010110111111	010011011110111101011101011111	010111111001011011010101111010
6	000111001111000110111101010011001111	010101110101010111011111110011001111	010011011011110010111001101111111111
7	001110010111110101011101010011000101011110	011010011011110010011101111110000101110111	001100000110010010111001100110001101100111
8	100110011000001110110001001000110001110010110101	010011111010110010000000101010000101111100010001	111000100100000111011111001011010110111100010111
9	001000000110101000100101010001101001011110100110110100	1000110010010100011111001001010110000000010010100101111	101101000010100110110100001010101000100010011101000000
10	001100000111010010010111010111100011010101101000101110110000	00000100100110110010100000011100100010000111001100000000000011	101101010110111111110001000111001000010001111001000000000001011
11	111011000000110111011110000010010110001110000111101010010001001110	101000110000111111111011001001110001101111110000001110010101101011001	11001001000111001010010001001001100010010010001100111000000100000000
12	111011011110100011100100001000110011110010100000011011100100010101001001	111010010100100100000100010000111011101100001001101101010101101010101110	110111100001100000100011000100001101111101001101101100010010010000011101

TABLE 3: Desired and obtained values of design parameters

Evolutionary Algorithm	φ in Degree	Peak SLL (dB) Desired	Peak SLL (dB) Obtained	Thinning %	Directivity Obtained
DE	$\varphi = 0^o$	-30.00	-25.0932	47.00	29.4935
	$\varphi = 90^o$	-30.00	-24.4202		
	$\varphi = 180^o$	-30.00	-25.0932		
	$\varphi = 270^o$	-30.00	-25.0932		
GA	$\varphi = 0^o$	-30.00	-25.3927	48.07	29.5269
	$\varphi = 90^o$	-30.00	-24.2762		
	$\varphi = 180^o$	-30.00	-25.3927		
	$\varphi = 270^o$	-30.00	-25.3927		
PSO	$\varphi = 0^o$	-30.00	-24.1303	51.28	28.6952
	$\varphi = 90^o$	-30.00	-22.1417		
	$\varphi = 180^o$	-30.00	-24.1303		
	$\varphi = 270^o$	-30.00	-24.1303		

TABLE 4: Obtained values of design parameter in arbitrary azimuth plane

Evolutionary Algorithm	φ in Degree	Peak SLL (dB) Obtained
DE	$\varphi = 30^o$	-20.3873
	$\varphi = 120^o$	-17.5490
	$\varphi = 210^o$	-20.3873
	$\varphi = 300^o$	-17.5490
GA	$\varphi = 30^o$	-18.0101
	$\varphi = 120^o$	-18.7835
	$\varphi = 210^o$	-18.0101
	$\varphi = 300^o$	-18.7835
PSO	$\varphi = 30^o$	-20.0693
	$\varphi = 120^o$	-16.6282
	$\varphi = 210^o$	-20.0693
	$\varphi = 300^o$	-16.6282

TABLE 5: Comparative performance of DE, GA, PSO and FA

Algorithm	Best Fitness (out of 20)	Worse	Mean	Standard Deviation
DE	103.3645	108.327	105.6252	1.4646
GA	96.449	101.5135	98.1177	1.4838
PSO	165.1119	172.765	168.5585	2.9156

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TABLE 6: Wilcoxon's two sided rank sum test

Comparison Pair	P-value
GA/DE	3.3918e-06
GA/PSO	3.3918e-06

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